SSD-TDR-64-23

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Prepared for COMMANDER, SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

SATELLITE SYSTEMS DIVISION • AEROSPACE CORPORATION

CONTRACT NO. AF 04(695)-269

DDC
JUN 8 1964

SSD-TDR-64-23

Report No.
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This technical documentary report has been reviewed and is approved.

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ABSTRACT

A simple method for predicting the penetration distance of highly underexpanded retrorocket exhaust plumes into an oncoming free stream is developed and compared with experimental data. It is shown that the measured jet penetration distance and the standoff distance of the free stream bow shock wave are predicted closely by computing the plume flow field, using the method of characteristics for an axisymmetric plume exhausting into still air at a pressure equal to the oncoming free stream static pressure. The method is applied to a single jet and to a cluster of n identical jets. For the latter, the cluster is considered to be an equivalent single retrorocket having the same mass-flow rate (and thus an equivalent diameter $(n)^{1/2}$ times as large as the nozzle exit diameter of a single rocket).

NOMENCLATURE

D = distance between retrorocket nozzle exit plane and free stream bow shock wave

d_e = retrorocket nozzle exit diameter

L = distance between retrorocket nozzle exit plane and interface (between primary and secondary streams)

M = Mach number

n = number of plumes in cluster

P = pressure

R = radius of cylindrical obstacle to free stream formed by cluster of n identical retrorocket plumes (see Figure 2)

X = distance between retrorocket nozzle exit plane and jet shock wave

γ = specific heat ratio

δ = distance between interface and free stream bow shock wave

μ = Mach angle = $\sin^{-1}(1/M)$

θ = divergence half-angle of retrorocket nozzle at exit plane

<u>Subscripts</u>

∞ = free stream conditions

e = jet conditions at retrorocket nozzle exit plane

j = jet conditions at jet shock wave

n = values for a cluster of n identical retrorockets

t = total or stagnation conditions

1 = values for a single retrorocket

CONTENTS

I. INTRODUCTION

The interaction between forward facing jets exhausting from, or adjacent to, a body and an oncoming free stream has been studied extensively. This situation occurs when using retrorocket thrust for such purposes as decelerating a vehicle, alleviating aerodynamic heating at the nose of a blunt body, and altering the pressure distribution and drag of a body (see Reference 1 for summary and bibliography). When a retrorocket is used adjacent to a vehicle, the exhaust plume affects heating of the vehicle skin by the plume, communication between the ground and the vehicle, and the trajectories of other bodies near the vehicle. Solutions to these problems require knowledge of the distance that retrorocket exhaust plumes penetrate into an oncoming stream.

Measurements of the penetration distance were made by several experimenters (References 2 through 6). It was shown (References 2 and 5) that the standoff distance of the free stream bow shock wave could be predicted accurately, using the measured penetration distance. Peterson and McKenzie (Reference 3) suggested using the method of characteristics to determine the plume flow field for this problem, but they did not apply their analysis to predict the penetration distance. Romeo and Sterrett (Reference 4) attempted to predict the penetration distance, using the two-dimensional method of characteristics to compute the plume flow field. However, an unknown parameter in their analysis was the ambient pressure acting on the plume, and their predictions were sensitive to this parameter. This is the result of applying the two-dimensional method of characteristics to an axisymmetric flow field.

This report presents a simple method for calculating the penetration distance for a single retrorocket, and for a cluster of n identical retrorockets. In this method, the following contributions which are essential to the solution of this problem are made:

a. It is pointed out that, for a highly underexpanded exhaust plume, the distance X to the jet shock, as predicted using the axisymmetric method of characteristics, is independent of the ambient pressure acting on the plume.

b. It is shown that the distance X for a cluster of n identical retrorockets can be determined accurately, using a modification of single plume results, thus eliminating the difficulty of computing the complex multiple plume flow field.

c. It is shown that the bow shock standoff distance (D) is predicted accurately by computing the plume flow field, using the method of characteristics for an axisymmetric plume exhausting into still air with pressure equal to the oncoming free stream static pressure.

The validity of this prediction method is demonstrated by obtaining close agreement between predictions and the available experimental data, in which parameters were varied over wide ranges.

II. METHOD OF CALCULATION

The flow model used in calculating the penetration distance of the retrorocket plume into the oncoming free stream is pictured in Figure 1. This idealized model assumes that the plume is an axisymmetric jet, expanding into an opposing uniform free stream of known Mach number and total pressure. The jet terminates when it reaches a mutual stagnation point with the free stream in which the total pressures of the two streams are equal. This mutual stagnation point is determined by assuming that the jet expands along the axis until a Mach number M_j is reached at which a normal shock wave will reduce the total jet pressure to a value equal to the total pressure following a normal shock wave in the free stream. (This jet shock wave is different from the Riemann wave (References 7 and 8) and occurs closer than the Riemann wave to the jet nozzle exit plane.) The distance X from the nozzle exit to the jet shock is calculated from the knowledge of the variation of axial Mach number in the plume. This model is described in more detail in References 1 and 5.

The variation of plume Mach number along the axis is determined by a method of characteristics flow field calculation for an axisymmetric plume with a constant pressure boundary (i.e., a plume exhausting into still air). If the nozzle is highly underexpanded, then the axial Mach number variation is independent of the boundary pressure. This was true of all the cases for which computations were made.

For a single jet, it was assumed that the plume forms an obstacle to the free stream in the shape of a sphere of radius L (the distance from the nozzle exit to the interface between the free stream and jet flows). This assumption has been shown to yield close agreement with measured free stream bow shock wave standoff distances, using experimentally determined values of L (Reference 2). Because the distance L that is to be used in calculating the standoff distance δ is itself dependent on δ (see Equation (1)),

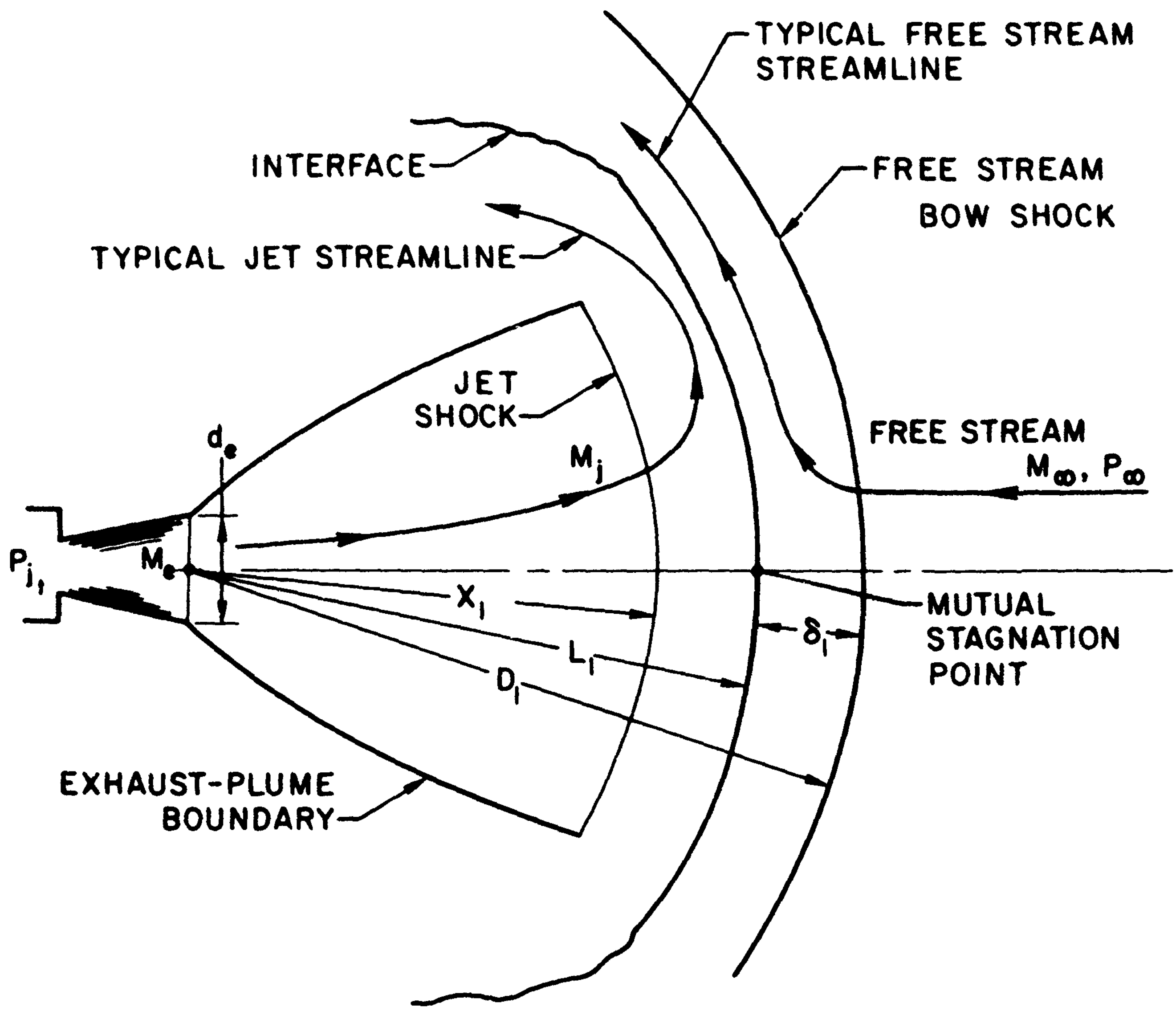

Figure 1. Flow Model for Single Jet.

the jet-shock distance X_1 can be used as an approximation to L, for high values of M_∞, for example, $M_\infty > 3$ (Reference 9). For low values of M_∞ ($M_\infty < 3$), an iterative process must be used. The bow shock wave standoff distance δ can then be determined for flow over a sphere of radius X_1, for low (Reference 9) or high (Reference 10) free stream Mach numbers.

The distance between the jet shock wave and the interface (between the primary and secondary streams) is assumed to be equal to δ. This assumption is based on experimental results (References 2 and 5). Thus, the total penetration distance L of the exhaust gases into the oncoming stream is given by

$$L_1 = X_1 + \delta_1 \tag{1}$$

and the distance to the free stream bow shock wave is

$$D_1 = L_1 + \delta_1 = X_1 + 2\delta_1 \tag{2}$$

III. EFFECT OF MULTIPLE JETS

Good correlation of the analytical calculation with the measured plume penetration distance of four clustered rockets (Reference 3) was achieved by multiplying the calculated single jet shock distance X_1 by the square root of the number of clustered rockets. This was derived by considering the cluster to be an equivalent single jet with the same total mass flow rate as the cluster of four jets. This equivalent single jet will have a nozzle exit diameter $(n)^{1/2}$ times as large as the nozzle exit diameter of each member of the cluster (where n = number of rockets in cluster), because the mass-flow rate through a nozzle varies as the square of the nozzle diameter. It is well known that physical dimensions of jets with equal nozzle exit conditions scale linearly with the nozzle exit diameter. In particular, the jet shock distance X scales in this manner. Thus, the jet shock distance for n retrorockets is

$$X_n = (n)^{1/2} X_1 \tag{3}$$

The above is a plausible, but certainly not rigorous, explanation of the multiple jet correlation factor, which is shown (in the next section) to be successful in obtaining agreement with the only available experimental data.

For a cluster of jets, the obstacle formed by the cluster of plumes is expected to be flat-nosed, rather than spherical, in shape (see Figure 2). It was assumed that the obstacle can be approximated by a cylinder whose axis is parallel to the free-stream direction. Good correlation with experimental measurements (Reference 3) was achieved by assuming the flat-faced cylinder radius R to be equal to the distance from the cluster centerline to the outer boundary of the cluster of plumes at station X_n.

The outer boundary of the cluster plume can be determined from the flow field calculation for an individual jet because the boundary of each of the four plumes would not be expected to be affected by impingement ~~of the plumes on~~ each other, as long as the intersection between the shock wave which is produced by impingement of the jets on each other and the jet boundary occurs downstream of X_n.

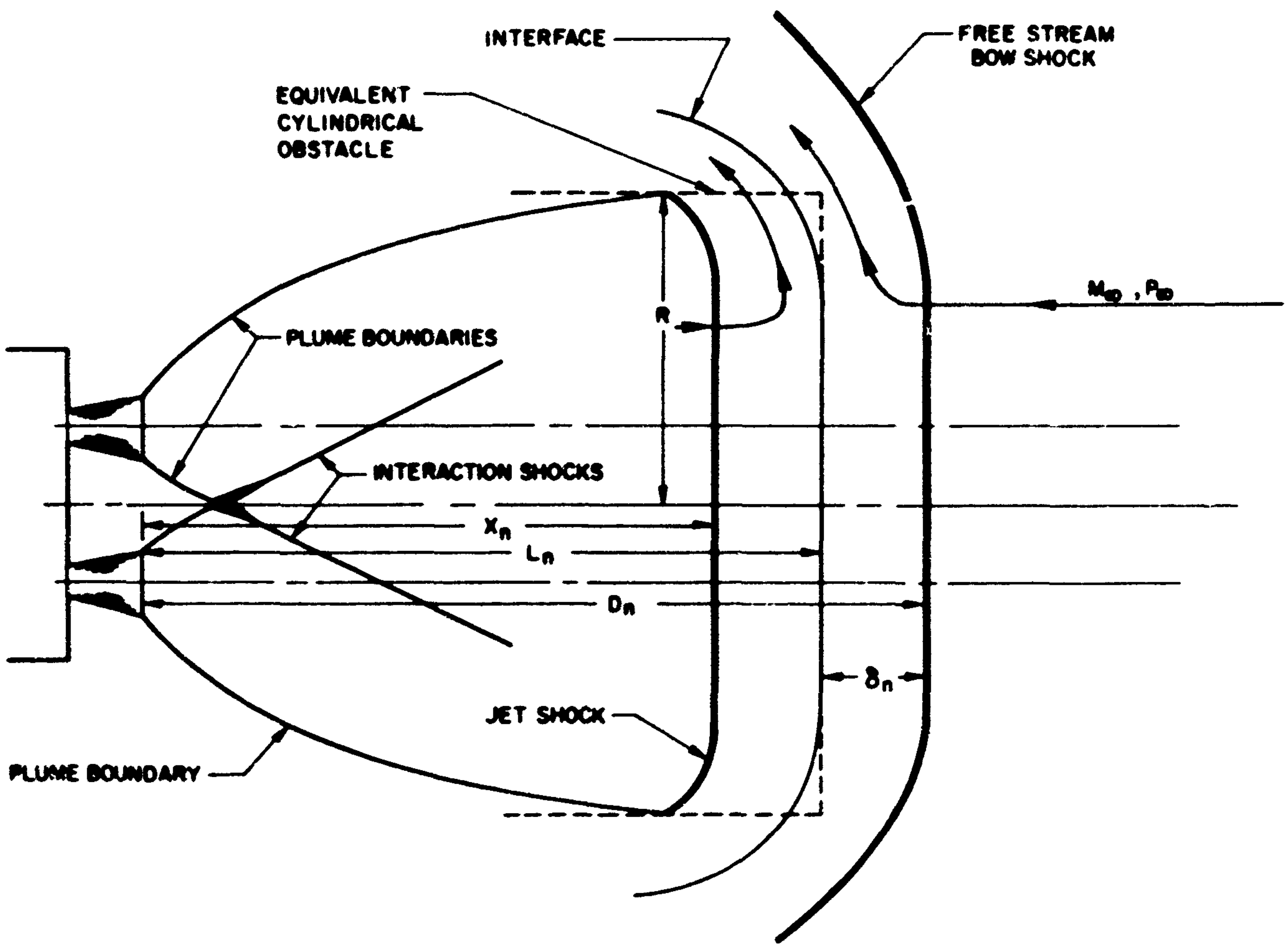

Figure 2. Flow Model for Clustered Jets.

Thus

$$L_n = X_n + \delta_n = (n)^{1/2} X_1 + \delta_n \tag{4}$$

and

$$D_n = L_n + \delta_n = (n)^{1/2} X_1 + 2\delta_n \tag{5}$$

where δ is determined from Reference 9 for flow around a flat-nosed cylinder of radius R.

Examination of Schlieren photographs (Reference 3) verified that each term in Equation (5) is predicted closely by this method. It should be noted that, for very highly expanded plumes, where the cluster plume radius is much larger than X_n, this procedure may not be applicable.

IV. COMPARISON OF CALCULATION TECHNIQUE WITH EXPERIMENTAL DATA

The calculation technique was compared with some available experimental data (References 2 through 4) to check the validity of the technique. The experiments were performed under a wide variety of conditions, so that a good test of the accuracy of the calculation method could be made. The supersonic jet data from Reference 2 and the data from Reference 6 were not used for this comparison because these plumes were overexpanded, or just barely underexpanded. The present study was restricted to plumes which are highly underexpanded, and the flow phenomenon for underexpanded jets is quite different from that for overexpanded jets (References 1 and 2).

The predicted and measured values of D are compared in Table 1. Note the reasonably close agreement between the theory and the experiment for the sonic jet tests (Reference 2) and the very close agreement for the supersonic jet tests (References 3 and 4). A possible explanation for the larger difference between theory and experiment for the sonic jet case than for the supersonic jet cases is the difficulty in computing the flow field in a sonic jet using the method of characteristics (Reference 8).

Table 1. Comparison of Predicted and Measured

Source of Data	M_∞	M_e	$P_{t,j}/P_\infty$	θ_e (deg)	d_e (in.)	Eq. used to Calc. D	X (the (i
Figure 8c, Reference 4 (single jet)	6.0	3.03	4000	18	0.107	2	0.
Figure 3c, Reference 3 (four-jet cluster)**	1.9	3.02	1345	15	0.412	5	3.
Figure 3a, Reference 3 (four-jet cluster)**	1.5	3.02	582	15	0.412	5	2.
Figures 17 and 18, Reference 2 (single jet)	2.91	1.00†	220	0	1	2	3.

* $\gamma_j = \gamma_\infty = 1.4$

** The retrorockets were placed 90 degrees apart on a circle with a di exit diameter

† A Mach 1.0038 jet (which corresponds to an exit Mach angle μ_e of 8 of a sonic jet (μ_e = 90 degrees), because of the difficulty of computi computer program (Reference 8)

†† The measured values of L also are given in Reference 2, and they

ed Shock Wave Detachment Distances.*

X_1 (theory) (in.)	δ (theory) (in.)	D (theory) (in.)	D (exp.) (in.)	Difference (%)
0.65	0.098	0.846	0.851	0.6
3.5	2.32	11.65	11.5	1.3
2.88	3.02	11.79	11.5	2.5
3.5	0.70	4.715	5.89	20.2††

a diameter 5.1 times the retrorocket nozzle

of 85 degrees) was used for this comparison instead
outing a sonic jet on the method of characteristics

ey are 13.2 per cent higher than the predicted values.

V. SUMMARY OF CALCULATION PROCEDURE

Close agreement was obtained between the predicted and measured values of D (distances between the retrorocket nozzle exit plane and the free stream bow shock wave) using the following technique:

a. Determine the plume flow field using the method of characteristics for a plume exhausting into still air whose pressure is the oncoming free stream static pressure.

b. Compute X by taking X as the axial station at which the plume has reached a Mach number M_j at which the jet will shock to a total pressure equal to the total pressure behind the free stream shock.

c. For a single jet, determine δ by assuming that the jet forms an obstacle to the free stream in the shape of a sphere of radius $X + \delta$ ($\approx X$ for large values of M_∞).

d. For a cluster of n identical jets, determine δ by assuming that the cluster forms an obstacle to the free stream in the shape of a flat-nosed cylinder whose radius R is the radius of an individual plume at station X_n plus the distance between the cluster centerline and the plume centerline.

e. For a single jet, compute D from Equation (2).

f. For a cluster of n identical jets, compute D from Equation (5).

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